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Strategic Petroleum Reserve (SPR) Long-Term Monitoring System Pressure Data Analyses*

Kent L. Biringer
SPR Geotechnical Division
Sandia National Laboratories
Albuquerque, NM 87185

Abstract

This report describes analyses of high-resolution pressure data collected on Caverns 2 and 110 at the Bryan Mound, Texas, Strategic Petroleum Reserve (SPR) site. A model of cavern pressurization is developed and applied to the two caverns. Use of the model to detect cavern pressure anomalies is demonstrated. Recommendations are provided for improvements in pressure monitoring and cavern operation to enhance the usefulness of pressure measuring as a tool in long-term cavern integrity monitoring.

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Introduction

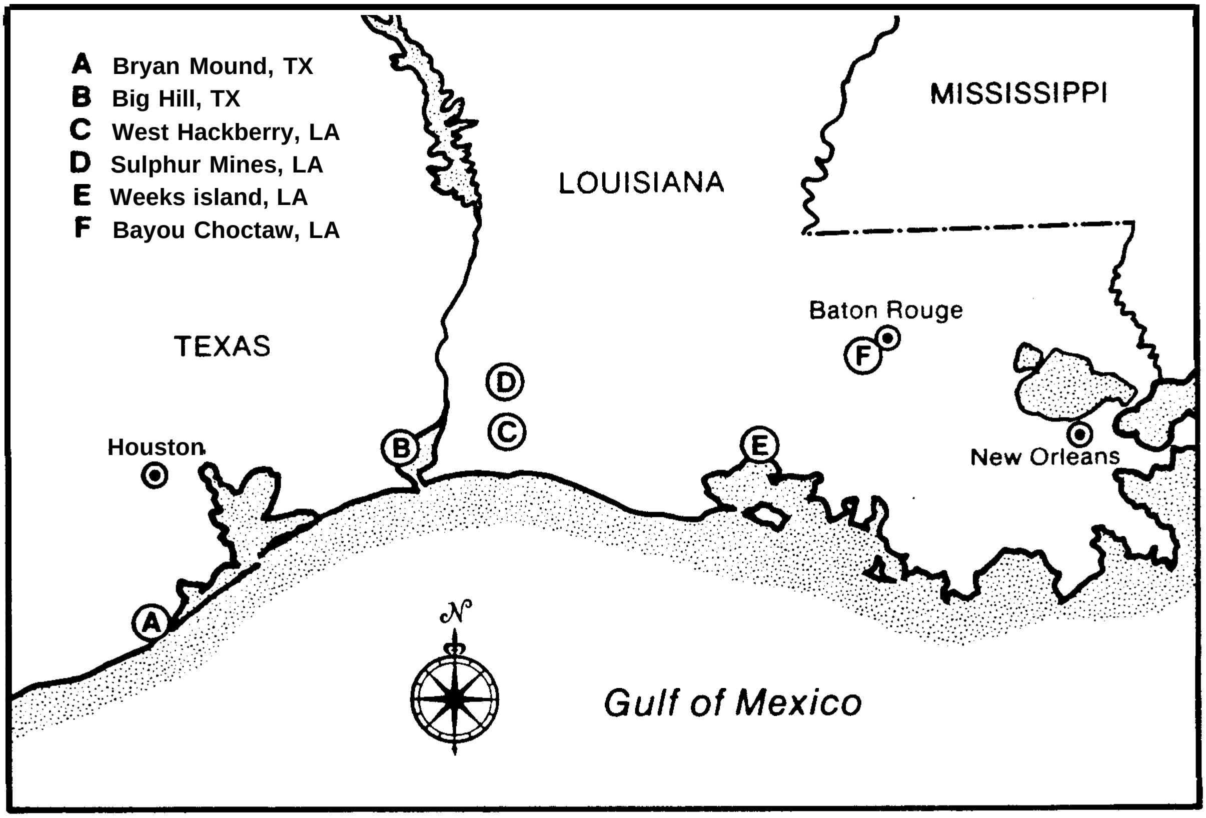
The United States Strategic Petroleum Reserve (SPR) consists of over 500 million barrels (MMbbl) of crude oil stored underground along the gulf coast in the states of Texas and Louisiana. Plans call for increasing the volume of oil stored to at least 750 million barrels. The reserve began in the mid-1970's in response to embargoes of oil from foreign suppliers. The reserve is intended to be used in times of national energy emergencies and is a key element in U.S. energy policy.

The oil is stored within geologic structures known as salt domes. About 15% of the oil is contained within a salt mine which was mechanically mined at Weeks Island, Louisiana. The remaining 85% of the oil is stored within caverns which have been leached into the salt. The leaching process uses water to dissolve the salt and create the large underground storage cavities. The leached caverns are at sites at Bryan Mound, Texas, and West Hackberry, Sulphur Mines, and Bayou Choctaw, Louisiana. One new site at Big Hill, Texas is currently starting to be developed. Figure 1 shows these site locations. Although further site and cavern development continues, most of the 500 million barrel current reserve is within storage caverns which have completed development. The majority of these caverns each contain 10 million barrels of oil and are nearly 2000 feet in vertical dimension. The role of monitoring and safeguarding the oil is a primary responsibility of the SPR program once development is complete. Pressure monitoring and analysis are key elements in helping to ensure the integrity of the storage volumes.

Once caverns are developed and filled they remain dynamic. Cavern pressures are affected by the heating of the oil due to temperature differences between the oil and formation, creep of the salt which is a plastic material, salt solutioning, operator induced pressure cycling to maintain pressures within prescribed ranges, and other pressure excursions due to oil transfers or cavern maintenance procedures. In addition, loss of oil due to leaks from the cavern or well will result in pressure changes. It is the objective of the work described in this report to evaluate cavern pressure histories and to develop models and operating procedures to enable operators to rapidly detect changes in cavern pressurization rates so that problems can quickly be recognized and corrected. The value of prompt detection can be measured in both the dollar value of oil saved as well as the value of avoiding environmental damage due to lost oil.

Some of the factors impacting pressure change occur quickly while others occur over a longer period. Therefore, developing a complete understanding of pressure changes within large storage caverns requires a long term evaluation of the factors influencing cavern behavior. With large storage caverns, small changes in pressure correspond to significant changes in oil volumes. In order to detect small pressure changes, a baseline of cavern pressure history needs to be established against which to compare. This report summarizes cavern pressurization histories on several SPR caverns based on data collected over a period of two years. Some baseline pressurization trends have been established and recommendations are provided on requirements for continued pressure monitoring.

FIGURE 1–
STRATEGIC PETROLEUM RESERVE STORAGE SITES



Objectives of Pressure Monitoring

The purpose of pressure monitoring is to ensure the integrity of the oil storage. This can be measured by several different pressure monitoring objectives.

The first objective is to identify sudden changes in cavern pressure which could be indicative of a breach of integrity due to items such as wellhead failure. These sudden changes may also be an indication of instrument failure or work on the well pad.

A second objective is to identify changes in long-term pressurization behavior. These may be indicative of cavern leaks which are more gradual and not otherwise detectable at the surface. This is the primary focus of this report.

A third potential use of cavern pressure data is to evaluate, on a continuous basis, changes which may occur to the level of the oil/brine interface. These changes can be detected by analyzing the differences between the oil and brine pressures. However, since this pressure difference is only 0.15 psi/foot, extremely accurate pressure and fluid property measurements would be necessary to provide a sensitive measure of small fluid changes.

Together, all of these objectives may be useful not only in detecting problems with the cavern near the time at which they occur, but also in ensuring the integrity of caverns to state or other officials who require that cavern integrity be demonstrated and certified.

SPR Cavern Creation and Operation

In order to better understand the objectives of the pressure monitoring system it is first necessary to understand the way in which the SPR oil storage caverns are created and operated.

The storage caverns exist as large underground cavities which have been created by dissolving salt with water. The process begins by first drilling a well into the salt and casing the well. This is typically at a depth of 2000 feet or greater. Drilling continues for an additional 2500 feet in the salt. A second smaller hanging string is suspended inside the cemented casing to near total depth. Surface water is injected through the hanging string. Salt along the wellbore is dissolved and near saturated brine is returned to the surface. This process creates a larger wellbore and eventually, over a period of two years, an entire cavern. The size and shape of the cavern are tailored by the flow rates, flow directions, and string settings. In some cases two or more wells are coalesced into a single cavern.

Oil is added through an oil string near the top of the cavern. The lighter density oil remains in the upper portion of the cavern with the denser brine in the bottom portion of the cavern. Unlike water, oil will not dissolve or react with salt. As oil is added, brine is removed from the bottom of the cavern through a brine string and the oil/brine interface moves down in the cavern. Figure 2 shows a typical SPR cavern configuration with the cavern oil-filled. Some brine remains in the bottom of the cavern. Portions of it will be periodically removed to reduce cavern pressures as the salt creeps and the oil expands with increasing temperature.

The oil and brine pressures measured at the wellhead can be used as a measure of downhole pressure conditions. The oil and brine surface pressures are related by the densities of the two fluids and by the depth to the oil/brine interface. These cavern pressure relationships are analogous to those of a simple manometer or U-tube pressure device. An example of the pressure relationships is shown in Figure 3. Brine and oil are the two fluids in the manometer. The oil side surface pressure is the sum of the brine head surface pressure and the difference between the densities of the two fluids acting over the depth to the oil/brine interface. Oil with a specific gravity of 0.85 has a pressure of about 0.37 psi/ft and brine with a specific gravity of 1.2 has a value of 0.52 psi/ft. The difference in pressure due to the two fluids is 0.15 psi/ft. In the example shown, the fluid column differences extend 4000 feet from the surface to the depth of the oil/brine interface. This results in a pressure difference of 600 psi between the oil and brine surface readings. As cavern pressures increase, the surface oil and brine pressures will increase at the same rate. Only changes in interface depth or fluid densities in the columns will change the 600 psi difference between the oil and brine values.

The Long Term Monitoring System

Sandia National Laboratories has been involved in the development and fielding of a computerized automated assessment system (CAAS) for monitoring cavern pressure data on four of the SPR oil storage caverns at the Bryan Mound site in Texas. This system became operational late in 1984 with most data collections beginning in January 1985. Four caverns at the site have been monitored for brine and oil pressures and gauge temperatures. In addition, temperature and barometric pressure at an instrument building have been recorded.

The four caverns selected for monitoring are Caverns 2, 101, 110, and 112. Cavern 2 was created as a result of brining operations prior to the SPR program. Caverns 101, 110, and 112 were all created specifically for SPR oil storage as described earlier and were all at different stages of development during the monitoring period. Figure 4 shows the location of all caverns at the site with the monitored cavern locations shaded. Table 1 lists the characteristics of these caverns. Figure 5 shows the vertical cross section profiles of each of these caverns.

Using the CAAS system, long-term monitoring (LTM) data were recorded every two hours. Periodically, the data were transferred via phone lines to a computer data base at Sandia in Albuquerque. The data were calibrated based on results of periodic calibrations of the field pressure transducers. In addition, a temperature correction was applied to the data based on the correlation of gauge temperatures and pressurization rates. These calibrated and temperature corrected two-hour data values were then averaged

FIGURE 2-
TYPICALSPR STORAGE CAVERN DESIGN

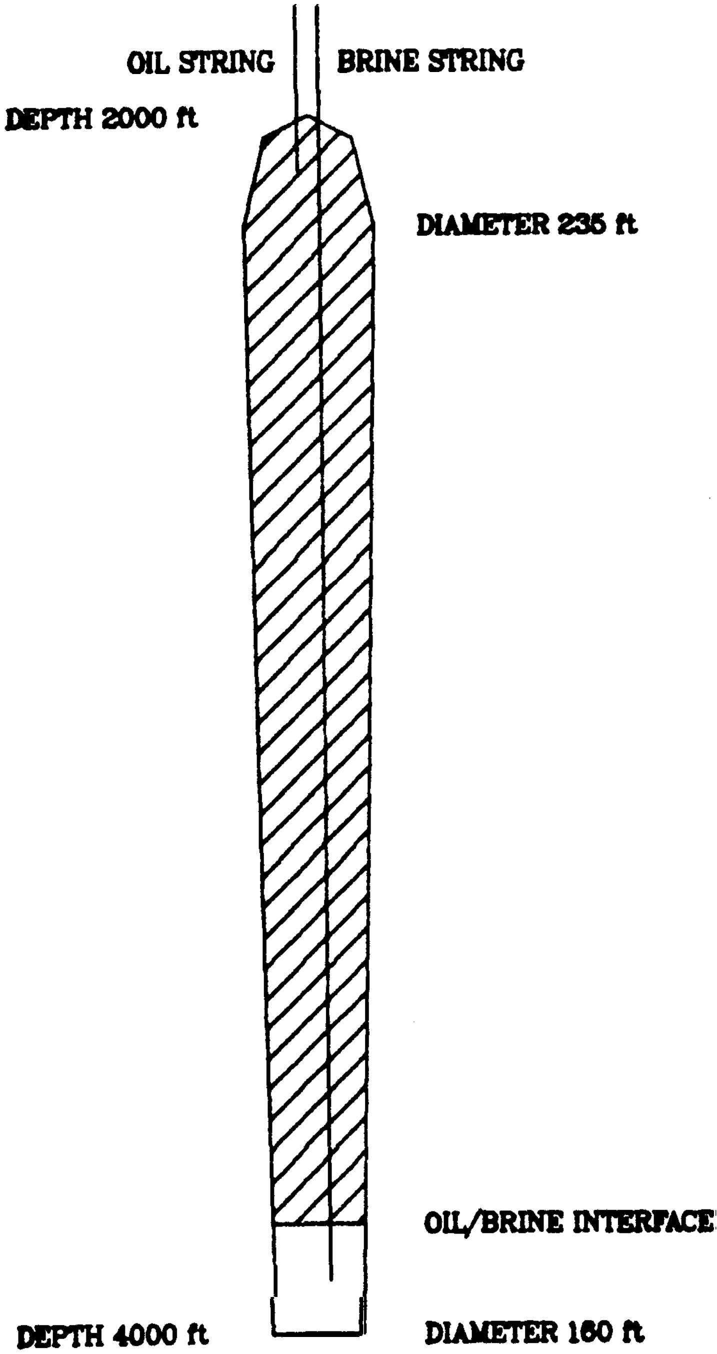
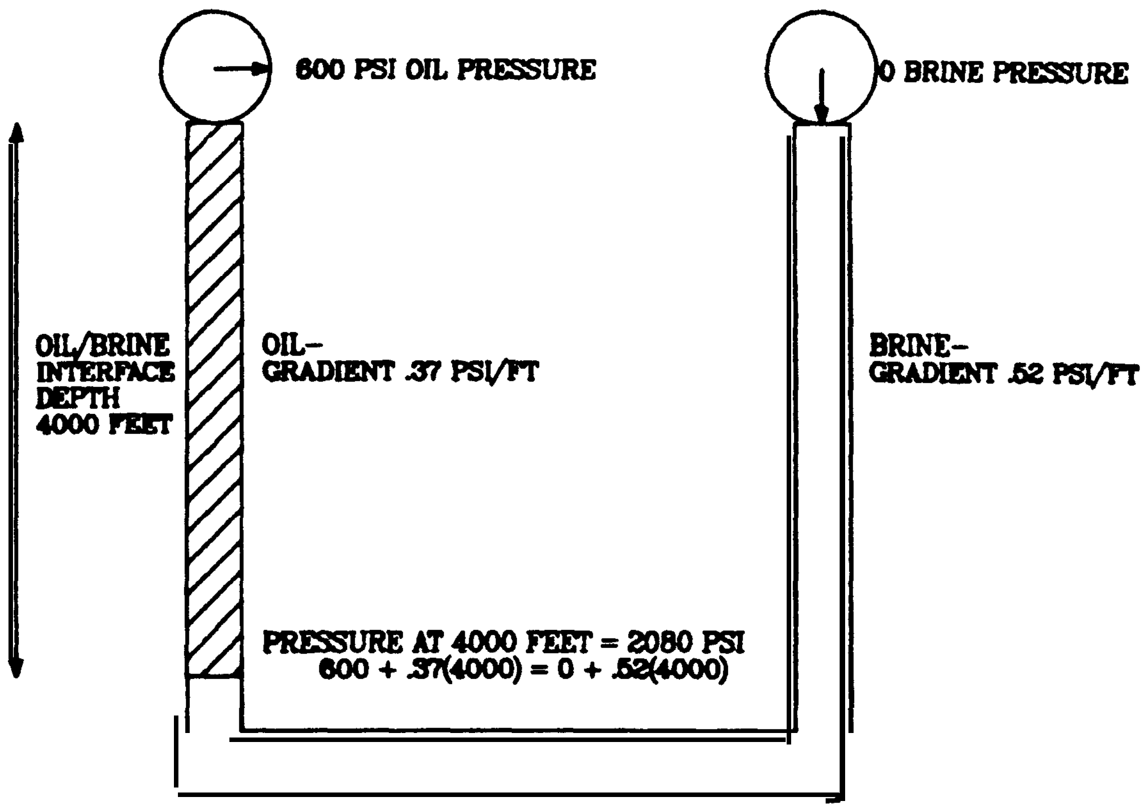


FIGURE 3–
CAVERN PRESSURE EXAMPLE



to provide daily pressure readings. It is these daily averages of calibrated data that form the data base analyzed in this report.

Temperature corrections were determined by using a linear regression fit of the two-hour pressure changes with the two-hour gauge temperature changes. During the two-hour time interval the temperature effects on pressure vary over a wider range than the other pressure parameters. This permits a single temperature correlation to be made over a wide range of pressure conditions. The correlations derived were -0.051 psi/degree F for the Cavern 2 oil pressure gauge and -0.028 psi/degree F for the Cavern 110 oil pressure gauge. Data on Caverns 101 and 112 have not yet been temperature corrected.

The goal of the analysis task is to develop a mathematical model of cavern pressure behavior which allows us to describe the observed pressure behavior based on known cavern physics, material properties and operational procedures. Such a model could be used to predict cavern behavior and to set alarms or flags when cavern pressures stray outside of prescribed boundaries.

Cavern Pressure Model

The plot of surface oil (or brine) pressure vs. time for an SPR cavern generally shows periods of pressure increase followed by abrupt decreases which correspond to pressure bleeddowns performed by site operators. Each of the pressure increase intervals has a profile with time which is influenced by the temperature, salt creep and operator influences already described. A generic pressure profile is shown in Figure 6. Pressurization and bleeddown intervals are labelled on the figure. The objective of this model development effort is to relate these cavern pressure cycles to known cavern influences and to develop a mathematical model describing and predicting cavern pressure behavior.

A number of models of cavern pressure behavior were analyzed. The model selected accounts for salt creep, fluid temperature influences and operator induced pressure changes. Salt solutioning which would occur following a drawdown using unsaturated water is not included in this analysis.

The model itself has been structured to calculate pressurization rate AP, defined as the daily change in cavern pressure. This proved to be a more useful measure of changes in cavern pressure than did absolute pressure since the absolute surface pressures are more subject to operator influence. For example, the depth of the oil brine interface has a large impact on the absolute pressure measured at the surface but a much smaller influence on the cavern pressurization rate.- The differential pressure also allowed for more easily determining the time constants corresponding to different pressure parameters. The pressure at any given time is the starting pressure plus the integral of AP over the interval. The pressurization model as described below has the form:

Table 1-

Bryan Mound Monitored Cavern Characteristics
(as of January 30, 1987)

Cavern Number	Well Number (MMbbl)	Cavern Volume (MMbbl)	Oil Volume (feet)	Roof Depth (feet)	Total Depth (feet)	Interface Depth (Year)	Start Fill (Year)	End Fill
2	2A	6.3058	5.8899	1450	1670	1640	1977	1977
101	101C	11.2578	11.0007	1998	4162	3995	1982	1986
110	110A	11.4450	10.6913	2114	4127	3796	1982	1983
112	112A	11.0680	10.6237	2065	4173	4058	1984	1986

FIGURE 4-
BRYAN MOUND SITE

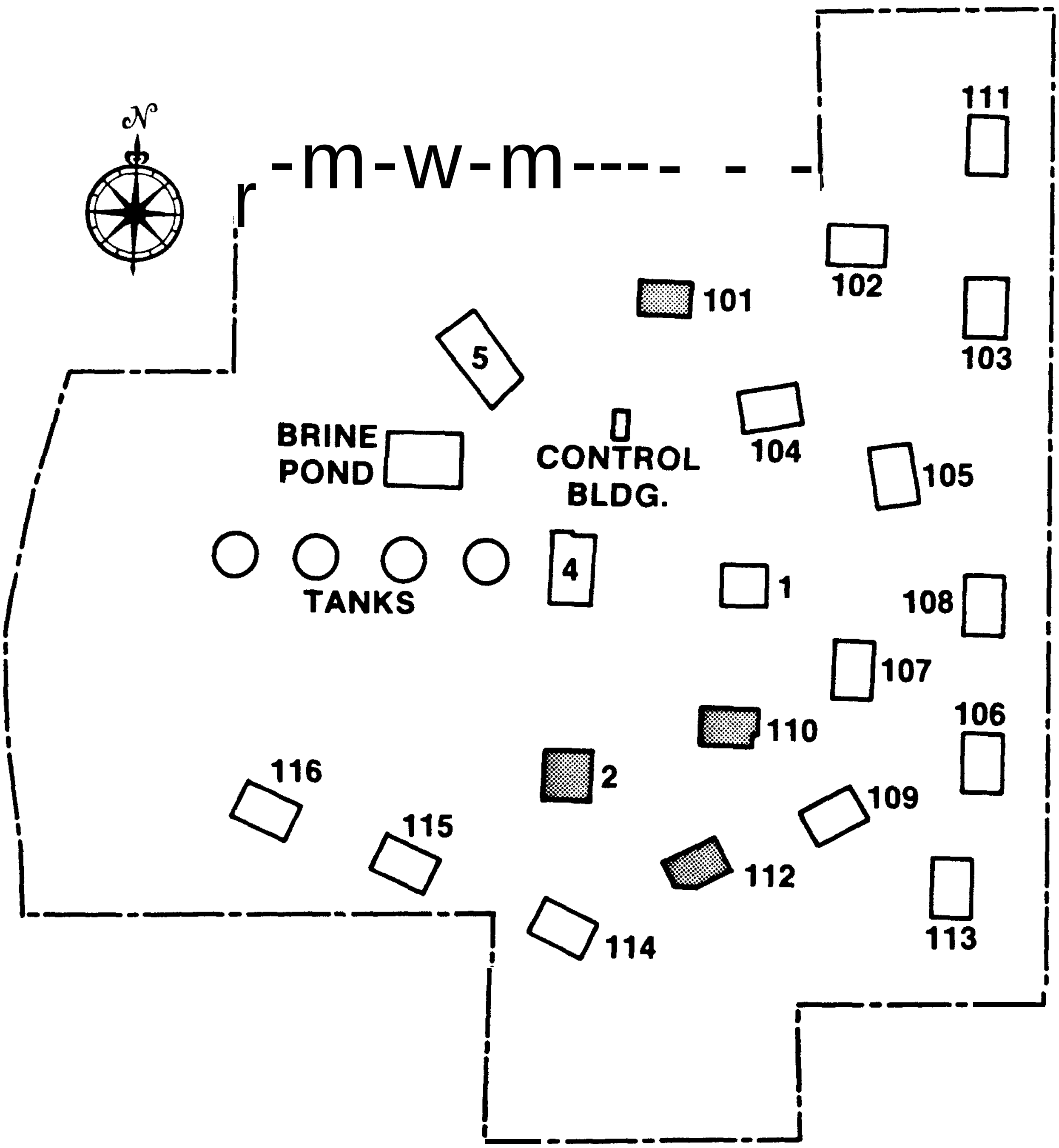


FIGURE 5-

LONG TERM MONITORING PROJECT PROFILES OF BRYAN MOUND CAVERNS MONITORED

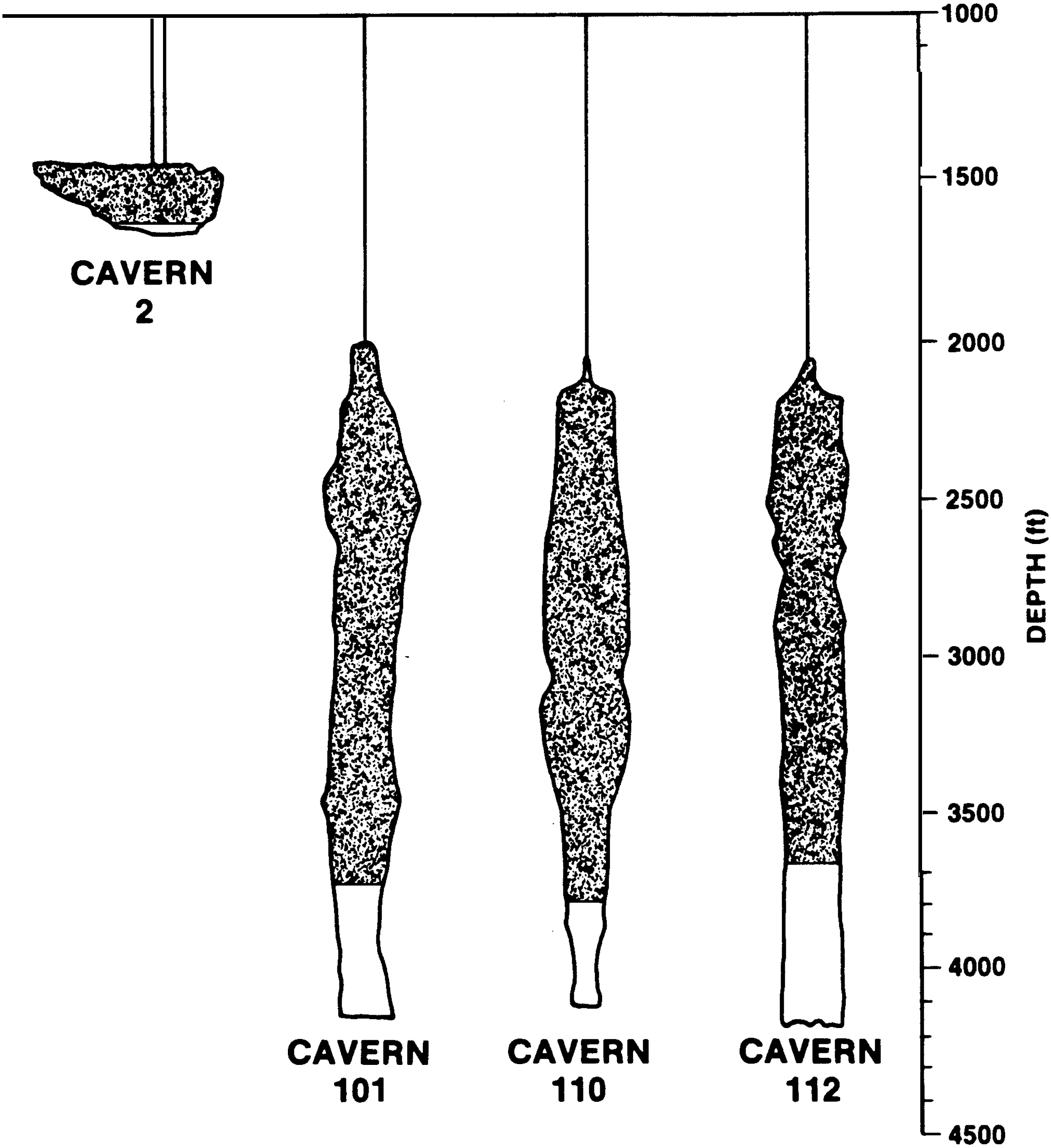
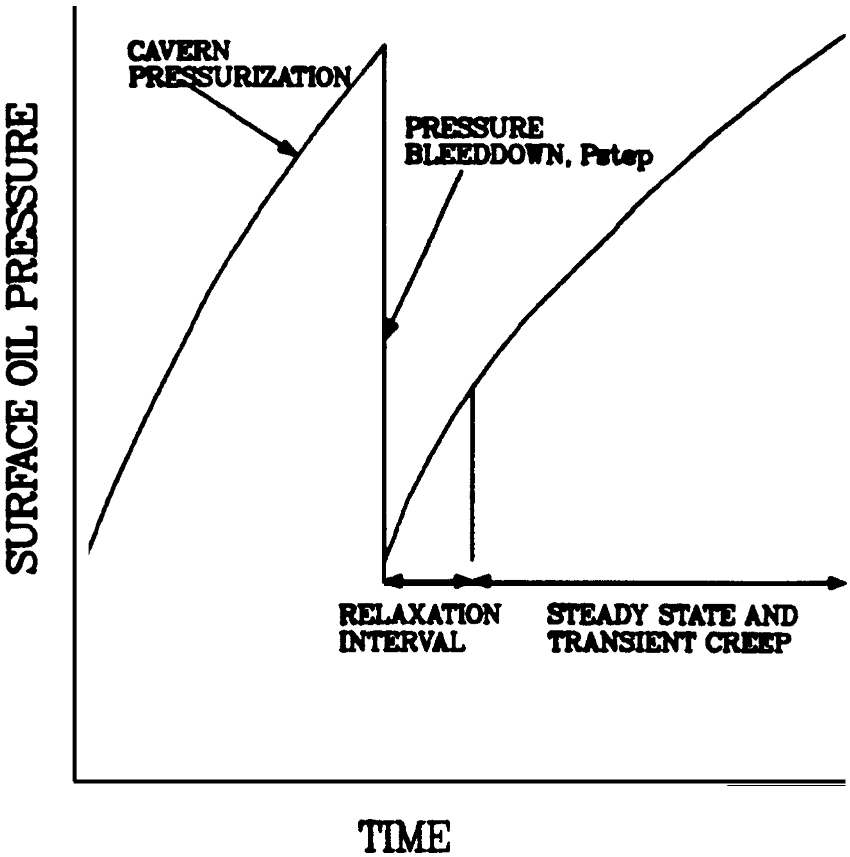


FIGURE 6–
TYPICAL CAVERN PRESSURE BEHAVIOR



$$AP-(A+Be^{-t/T1}-C*Pstep*e^{to/T2})*\left|\frac{Pf-P}{Pf-Pref}\right|^{n}+De^{-t/T3}$$

where:

A is steady state creep constant, psi/day
B is transient creep constant, psi/day
C is relaxation constant, l/day
D is thermal expansion constant, psi/day
T1 is transient creep time constant, days
T2 is relaxation time constant, days
T3 is thermal expansion time constant, days
Pstep is the magnitude of a sudden pressure change (negative if pressure decrease), psi
Pf is the product of depth and the difference between lithostatic and fluid pressure gradients, psi
P is the current surface oil pressure, psi
Pref is the reference surface operating pressure, psi
n is the creep exponent
t is a measure of time from the beginning of the data, days
to is the time since the last pressurization or bleeddown, days

The first term in the model is that of steady state creep. It is constant with time for a given stress level in the salt [l]. The second effect is one of transient creep which is modeled to decay exponentially [1] and which has a time constant on the order of 100's of days from the time of cavern creation. The final salt creep phenomenon in the model is a relaxation effect which results in shorter term (days to weeks) changes in pressurization rate due to abrupt changes in absolute cavern pressure. This is a phenomenon which has been observed in salt but which is not well documented. In this phenomenon, a rapid drop in cavern pressure is followed by an increased rate of pressurization, while a rapid pressurization is followed by a period of slower than normal pressurization. This accounts for the negative sign in front of the C coefficient since pressure increases are measured as positive. Figure 6 illustrates the higher pressurization rate immediately after a bleeddown. The steady state and transient creep components are difficult to distinguish over a single pressurization interval but can be measured by watching the pressurization rate decay through subsequent intervals. The creep models used here relate creep and pressure proportionally. For the small amounts of creep characteristic of large SPR caverns (about 1 inch per year out of a cavern radius of over 100 feet), the volume change of the cavern is proportional to the creep rate. This volume decrease due to creep results in a cavern pressure increase. The volume and pressure changes are related by the cavern elasticity which is a measure of the fluid volume required to achieve a 1 psi pressure change.

All of the creep terms are multiplied by a term which reflects the relative stress levels in the salt. Theory of salt behavior has shown that creep is driven by salt stress. This has been modeled as a power law relationship with creep proportional to the quantity stress divided by shear modulus to the nth power as described by Wawersik [1]. Since absolute values of in situ stresses are difficult to obtain, the pressure difference between the salt and the cavern fluid is used as the measure of stress. The lithostatic pressure is taken as the depth, d, multiplied by the lithostatic pressure gradient, gl, of 1 psi/foot. The fluid pressure in the cavern is the product of depth and the fluid gradient, gf, added to the fluid pressure at the surface, P. Therefore, the salt stress, σ, is proportional to:

$$d*gl - (d*gf + P)$$

By defining Pf to be the product of depth and the difference in lithostatic and fluid gradients, this expression reduces to Pf-P. By taking the ratio of stresses for different surface pressures, a relative measure of stress influence on the creep terms can be derived. As the surface pressure changes from a reference value all of the creep terms are multiplied by this stress effects term. The depth used for these calculations is the average cavern depth which is representative of the average stress levels in the cavern. Laboratory work on salt has resulted in creep models which *are* largely empirically based. Many values such as that of the creep exponent are not absolutes but vary from sample to sample. The selected value of 4.7 is an intermediate range value of those obtained for salt core samples from Bryan Mound [1].

The final pressure effect in the model is that due to heating of the oil. The oil entering the cavern is generally cooler than the lithostatic temperatures associated with the cavern depths of the SPR program. As the oil remains in the cavern, heating takes place. This heating results in increased cavern pressure determined by the coefficient of thermal expansion for the oil.

Therefore, the model developed here is based on changes occurring over four different time horizons by four different influences. These are: 1) steady state creep effects occurring uniformly over long periods of time; 2) transient creep due to initial disturbance of the salt measured over 100's of days; 3) salt relaxation due to sudden pressure changes occurring over a period of days to 10's of days; and, finally, 4) thermal heating of the oil occurring over a few thousand days.

Application of the Pressure Model

The two caverns which have been analyzed to date are Caverns 2 and 110. These two caverns differ significantly in their history and operation and these differences are readily seen in the cavern pressure histories over the past two years. A summary of cavern operation during this period is provided in the appendix. Table 2 lists the parameter fits used for the two caverns. The model fits and parameter selections were made based on the LTM data collected from the CAAS system. Although there is general agreement between the site data and the LTM data, there are some differences. Some of these differences are as a result of differences in data resolution as described later, while other differences may be a result of gauge calibrations or other factors.

Cavern 2-

The cavern pressure history from reported site data for Cavern 2 is shown in Figure 7 [2,3]. An expanded scale plot of the data showing both the site and LTM data is shown in Figure 8. The site data shows a step increase in pressure for several months from February 1986 through September 1986 followed by a similar step decrease. It is likely that an improperly calibrated gauge may have been installed over this period of time since this effect is not observed in the site brine data or the LTM data. The shallow Cavern 2 has a very low pressurization rate of less than 0.1 psi/day over the two year interval. This is due largely to the lower creep rates which occur under less stress at the shallower depths. However, it is also impacted by the fact that this cavern has existed for many years so that the shorter term transient creep effects do not appear to be present. In addition, the oil temperature is near equilibrium since the cavern is shallow and has lithostatic temperatures near those of the oil stored. For this reason the temperature coefficient for the Cavern 2 model was taken to be zero. The values of the creep exponent n were taken as representative of results of salt core analysis [l]. Figure 9 is a plot of the model and the LTM data for Cavern 2. The fit to Cavern 2 oil pressure data follows the LTM data very well over the first 18 months with an R squared correlation of better than 0.98. However, the data near the end of the interval shows a discrepancy with the model. Starting in mid-May of 1986 the cavern pressure is higher than that of the model. This may reflect an undocumented operational change or an incompleteness in the model. Due to the low pressurization rate of this cavern, only two pressurization intervals were available on which to base the model. In addition, transducers for the LTM system were disconnected during the period of transition of pressure slope. The measured pressurization at the end of the interval does not diminish to the extent expected by the 4.7 exponent power law measure of creep. However, despite the discrepancy near the end, the model accurately matches recorded data to within less than 1 psi over 18 months and to within 5 psi over the entire two year period.

Cavern 110-

Cavern 110 is a deeper cavern with the associated higher stress levels and creep rates. It is also a new cavern with transient creep effects still present and oil still heating. The temperature coefficient and time constant for Cavern 110 were calculated based on present oil temperatures and expected oil temperatures using results reported by Tomasko [4] and temperature and elasticity values reported by Linn [5]. The site pressure data for the two-year period are shown in Figure 10. An expanded scale view of site data is included as Figure 11. The pressurization for this cavern is nearly 1.5 psi/day at the start of the two-year recording period and diminishes to about .75 psi/day by the end of the interval. Figure 12 is a plot of the model fit and the site data for Cavern 110. Although there is general agreement between the model and the data, there are time intervals of exception. One of these is between June and August of 1985. The model indicates a continued pressurization during this interval while the data do not. A closer look at operational records indicates that a motor-operated value on the brine line was leaking during this period and, therefore, pressure was allowed to float on the brine line. During this period there was no chance

Table 2-

Model Parameters

		Cavern 110	Cavern 2
Steady State Creep Coefficient (psi/day)	A=	0.25	0.07
Transient Creep Coefficient (psi/day)	B=	0.65	na
Transient Creep Time Constant (days)	T1=	300	na
Relaxation Coefficient (l/day)	C=	0.004	0.0006
Relaxation Time Constant (days)	T2=	18	60
Thermal Expansion Coefficient (psi/day)	D=	0.4	0
Thermal Time Constant (days)	T3=	2500	2500
Final Pressure (psi)	Pf=	1890	983
Reference Pressure (psi)	Pref=	700	350
Creep Exponent	n=	4.7	4.7

FIGURE 7-

CAVERN 2 SITE OIL PRESSURE DATA

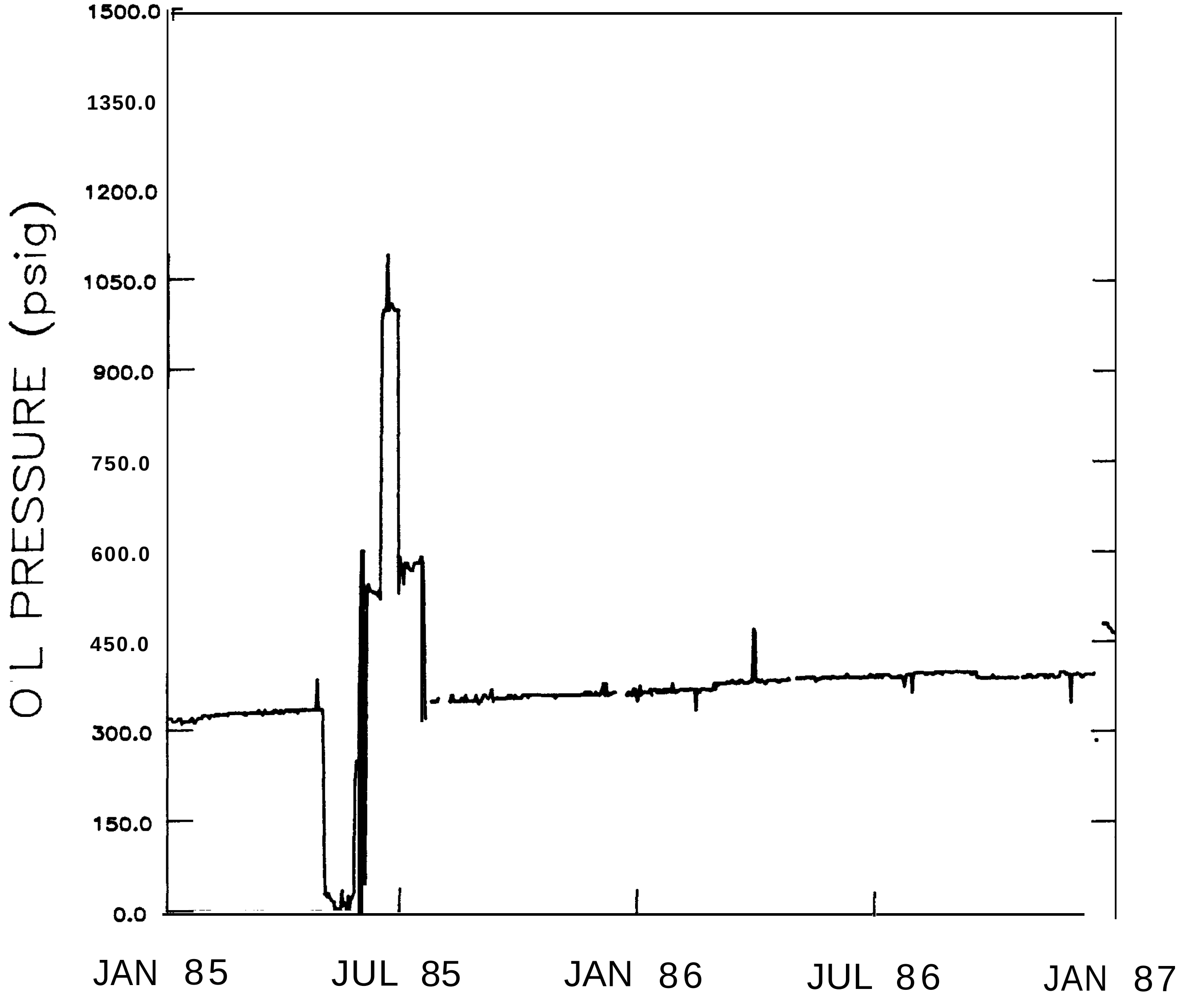


FIGURE 8 -

COMPARISON OF CAVERN 2
LTM AND SITE OIL PRESSURE DATA

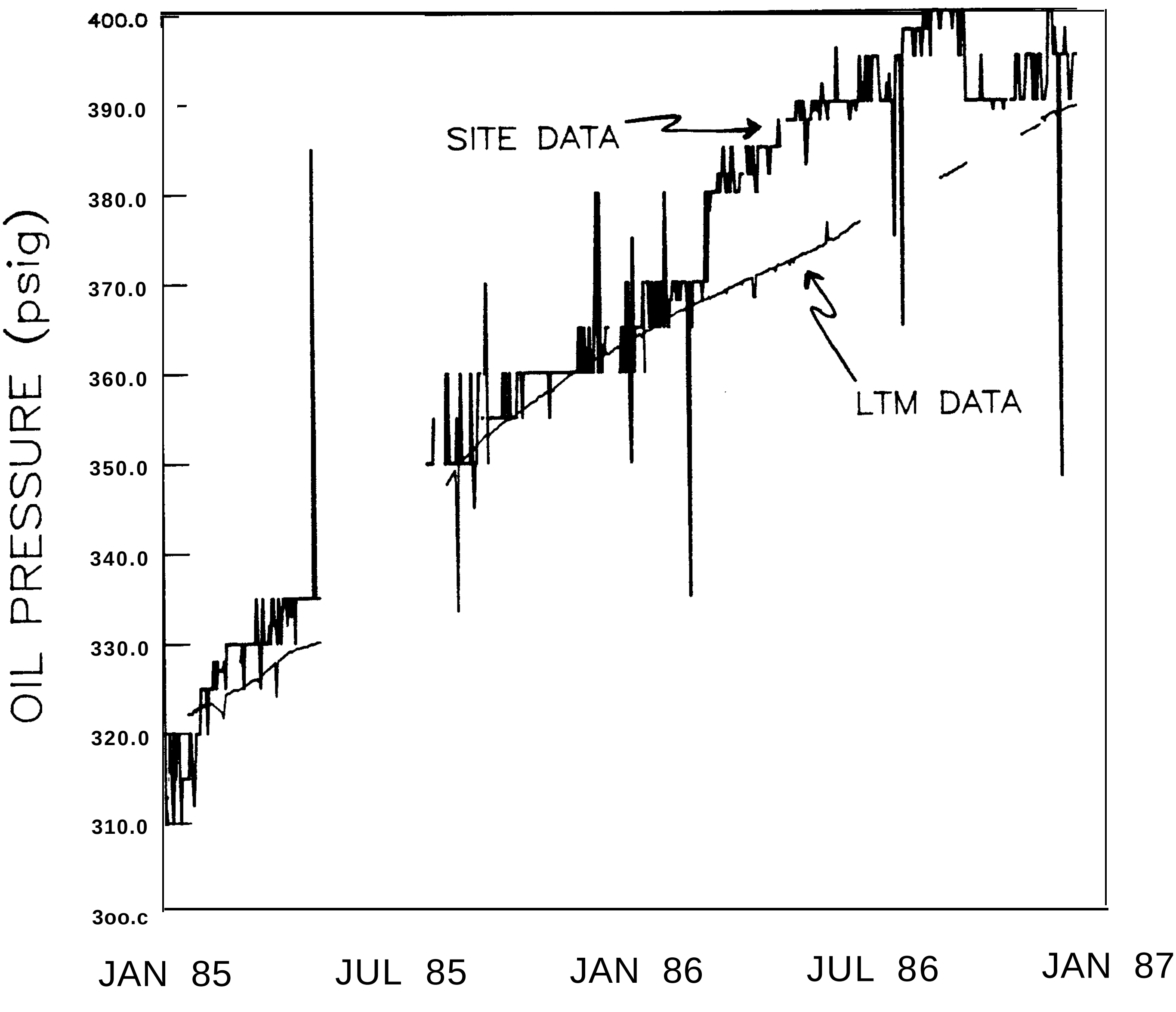


FIGURE 9—

COMPARISON OF CAVERN 2
LTM AND MODEL OIL PRESSURE DATA

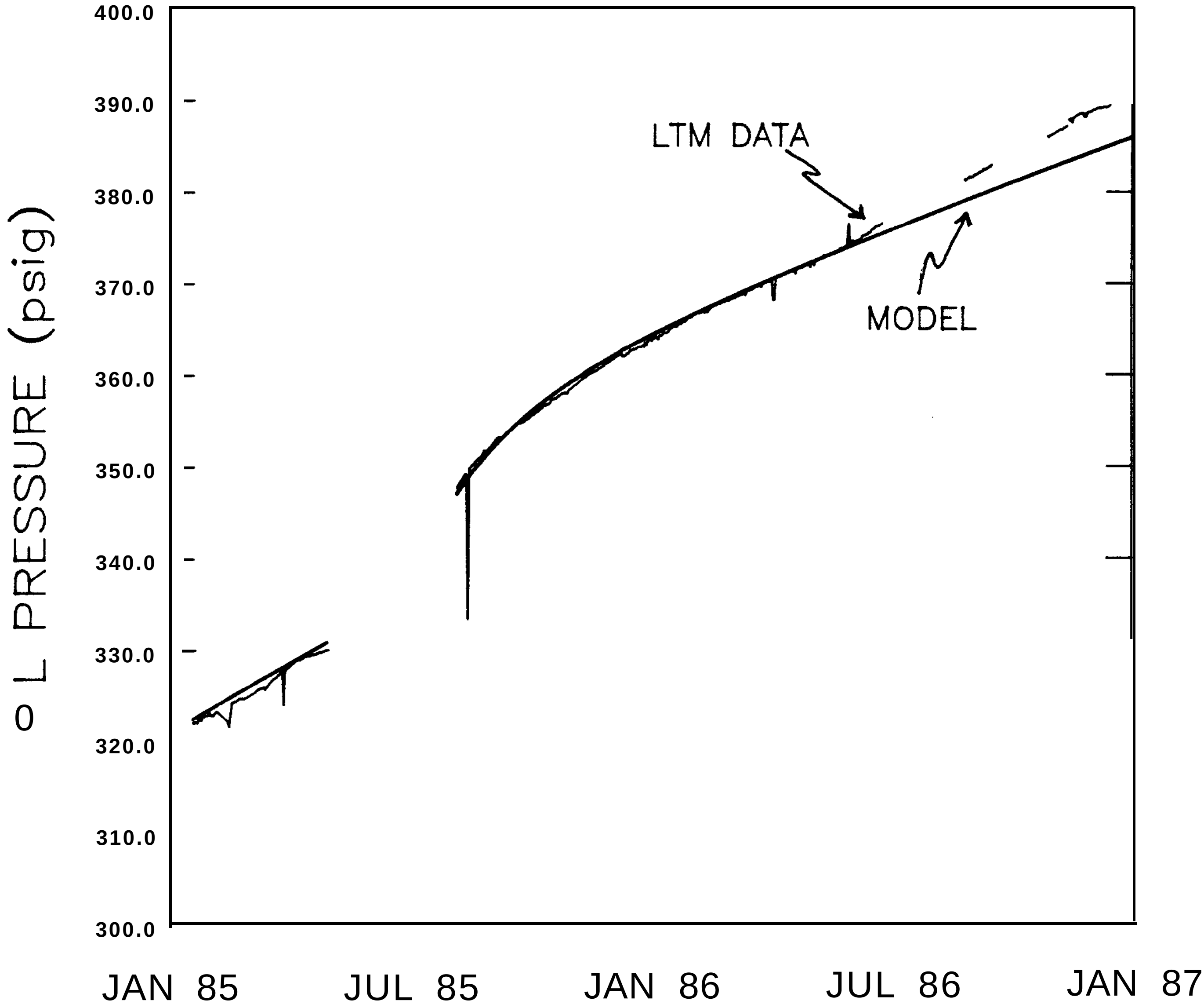


FIGURE 10–

CAVERN 110 SITE OIL PRESSURE DATA

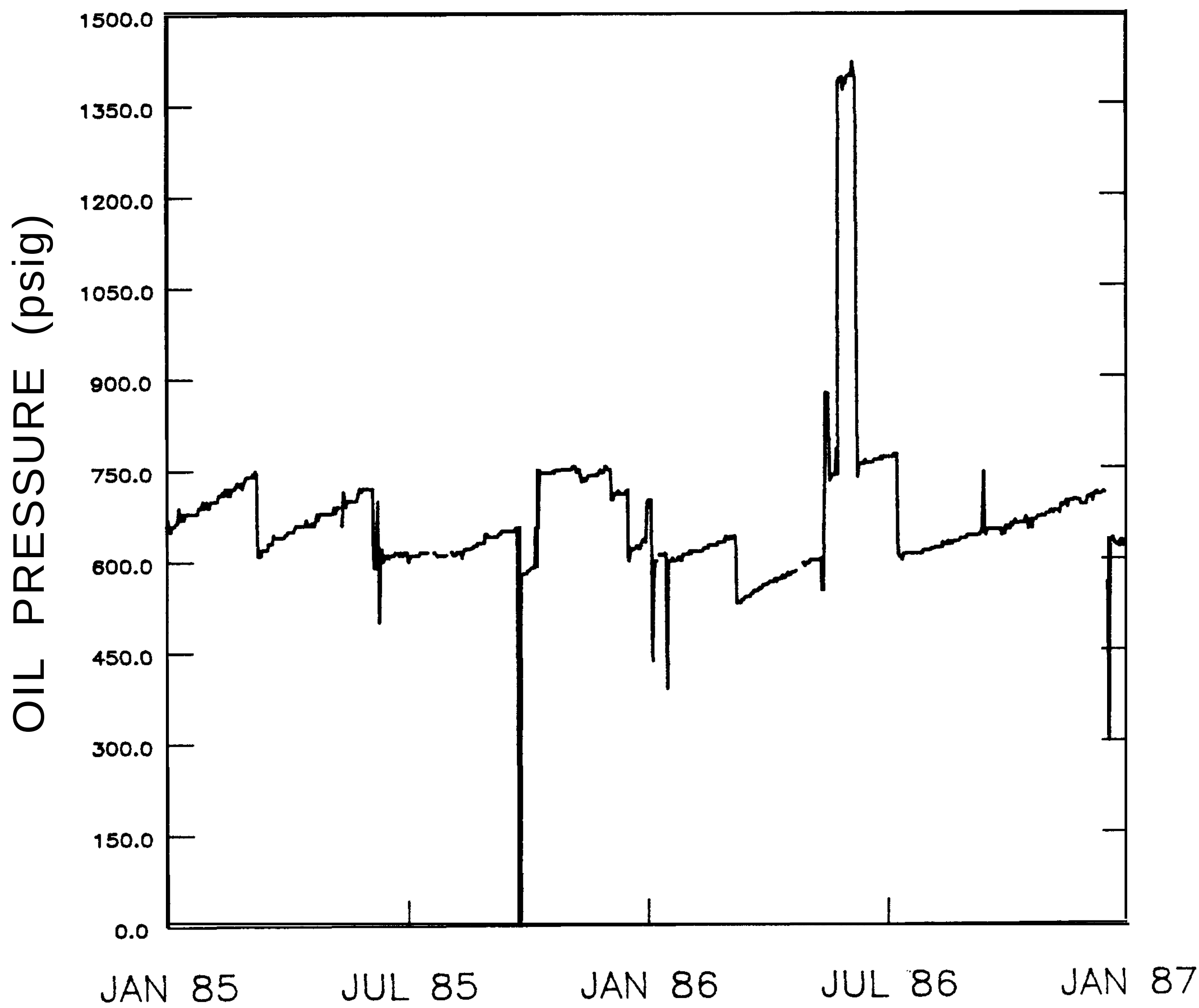


FIGURE 11-

EXPANDED SCALE CAVERN 110
SITE OIL PRESSURE DATA

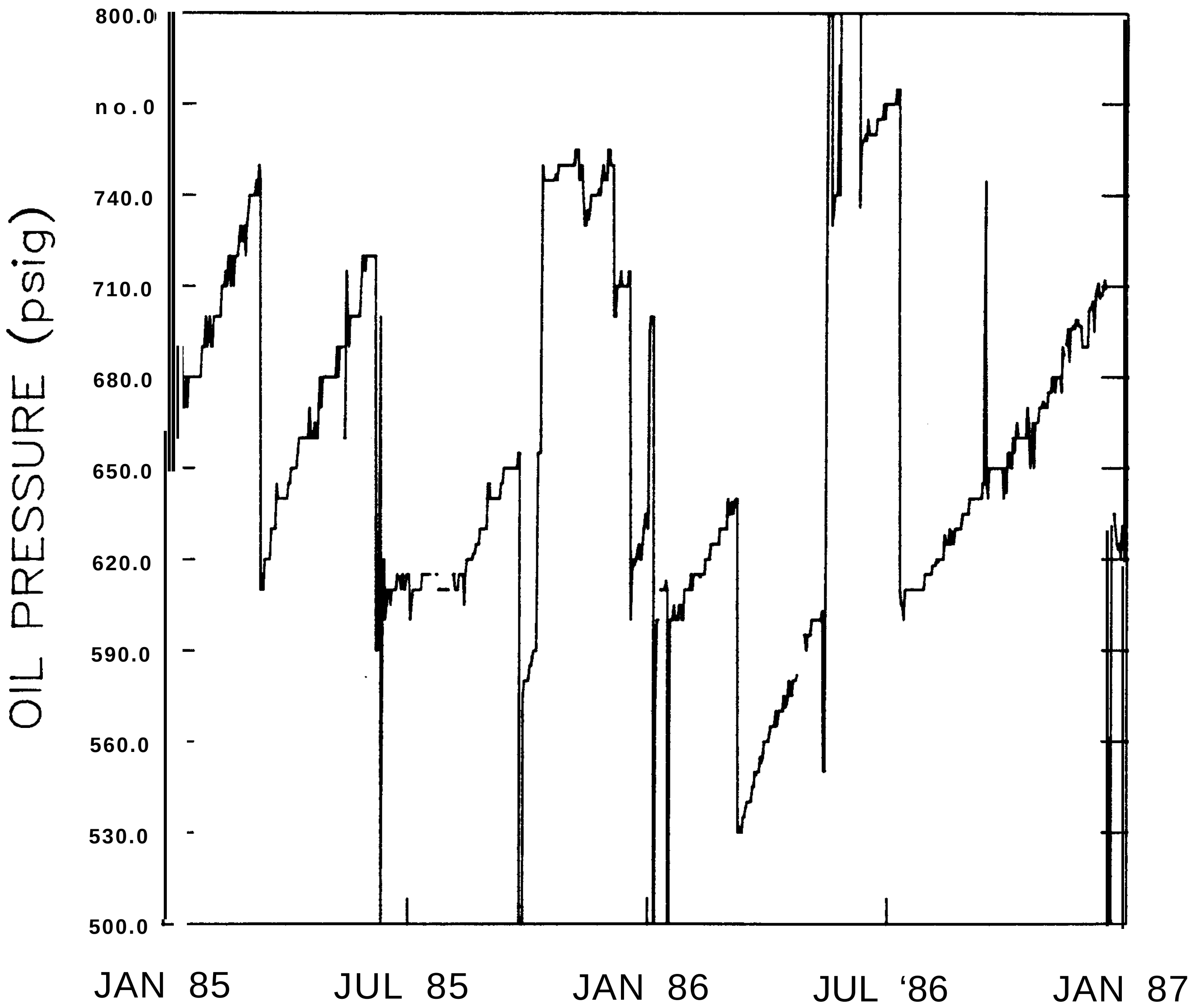
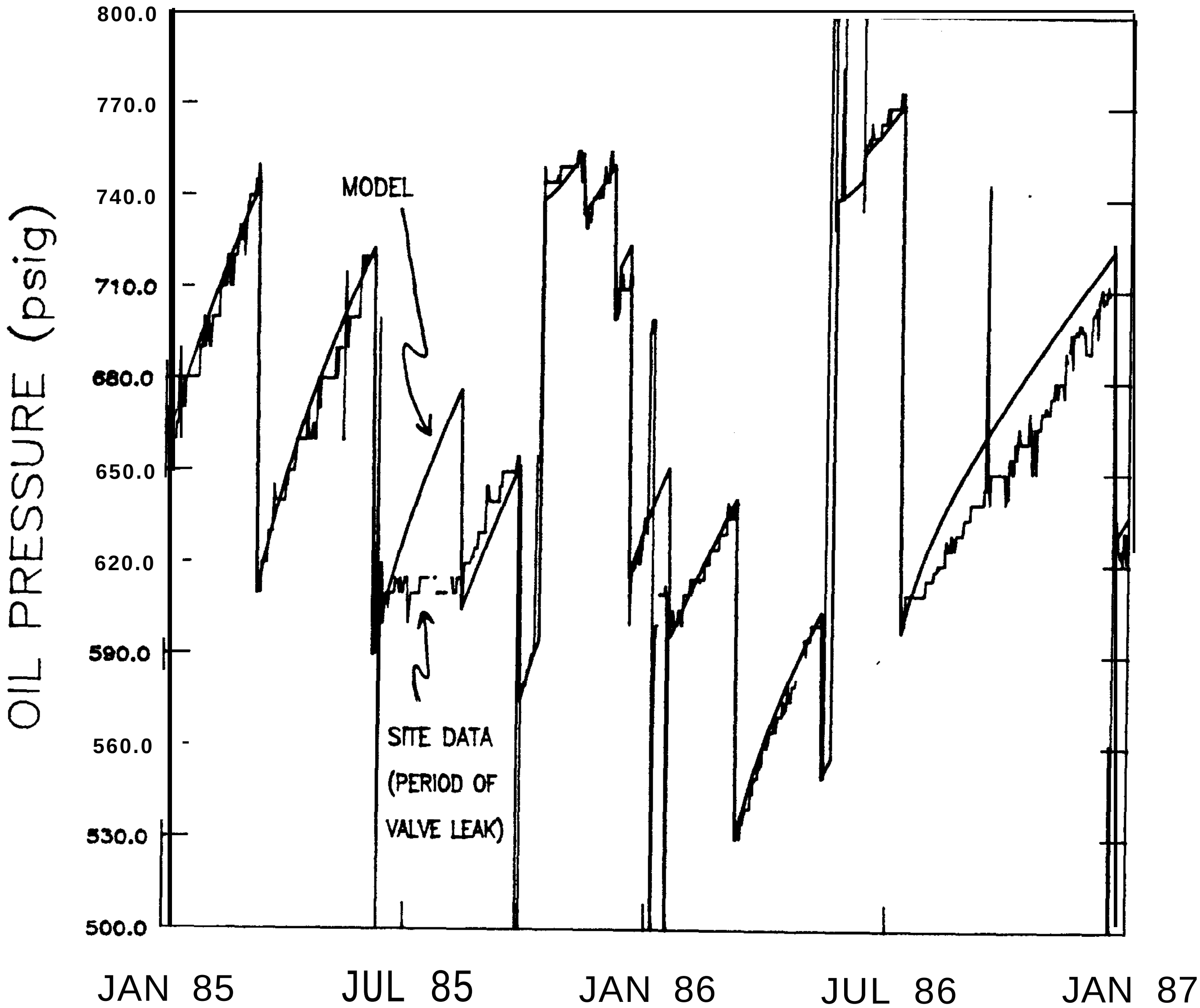


FIGURE 1 2-

COMPARISON OF CAVERN 1 IO
SITE AND MODEL OIL PRESSURE DATA



in which to use pressure measurements as a means of detecting fluid loss. Similarly, after a cavern pressurization test in July of 19.86, there again appears to be a discrepancy between the model and the data. It appears that for a period of time a valve was again leaking or other fluid loss was present.

The results indicate that fits to within 1 to 5 psi are achievable with this model. This level of detail allows one to evaluate cavern operation over the two-year period and detect intervals in which anomalous cavern pressures occurred. It is expected that continued model improvements can be made as more data are collected. A data base sufficient to ensure completeness of the model can be established only by taking data over still longer periods of time and by comparing data taken from a number of caverns.

Data Resolution

One requirement for modeling and for achieving accurate pressure monitoring is to collect high resolution pressure data. This means collecting data that are accurate to within about 1 psi. Current site data are primarily read manually from wellhead gauges to an accuracy of +/- 5 to 10 psi. Although this is adequate resolution to detect major pressure anomalies, it makes it much more difficult to detect subtle changes in pressure. Since a typical cavern elasticity is about 60 bbl/psi, each psi of pressure change is equivalent to 60 bbl of fluid. A deviation of 5 psi from an expected pressurization is equivalent to an uncertainty of 300 barrels of fluid. The higher the resolution the sooner any deviation can be detected. This can be shown by looking at Figure 13 which compares the LTM data and the reported site data for Cavern 110 over a period of about four months. On this expanded scale the LTM data show a steady pressure increase while the site data reflect the scatter of individual readings. The impact of this can be seen for the late October period when the pressure reading suddenly drops by 20 psi as shown in the highlighted area of Figure 13. If this were a true drop in cavern pressure, it would be equivalent to a loss of 1200 barrels of fluid. This was clearly not the case as evidenced by subsequent readings, but the inability to discern that for several days limits the usefulness of such pressure data in identifying anomalies that could be indicative of cavern leaks.

Another way of viewing the improved monitoring possible with higher resolution data is to plot the daily pressure change over the two-year period. Figure 14 shows this for Cavern 110. The manually read site data generally fall along lines at 0, +/- 5, and +/- 10 psi which reflect the resolution of the pressure gauges. The higher resolution LTM data show both the more representative daily pressure changes of 0.8 to 2 psi and the changes in pressurization which result from bleed downs or other operational impacts.

Similar differences in resolution can be observed in the differences between oil and brine pressures. These may be useful in helping to detect movement of the oil/brine interface, although other factors such as fluid densities can have a significant impact on that measure. Since a 1 psi

FIGURE 13-

COMPARISON OF CAVERN 110
LTM AND SITE OIL PRESSURE DATA

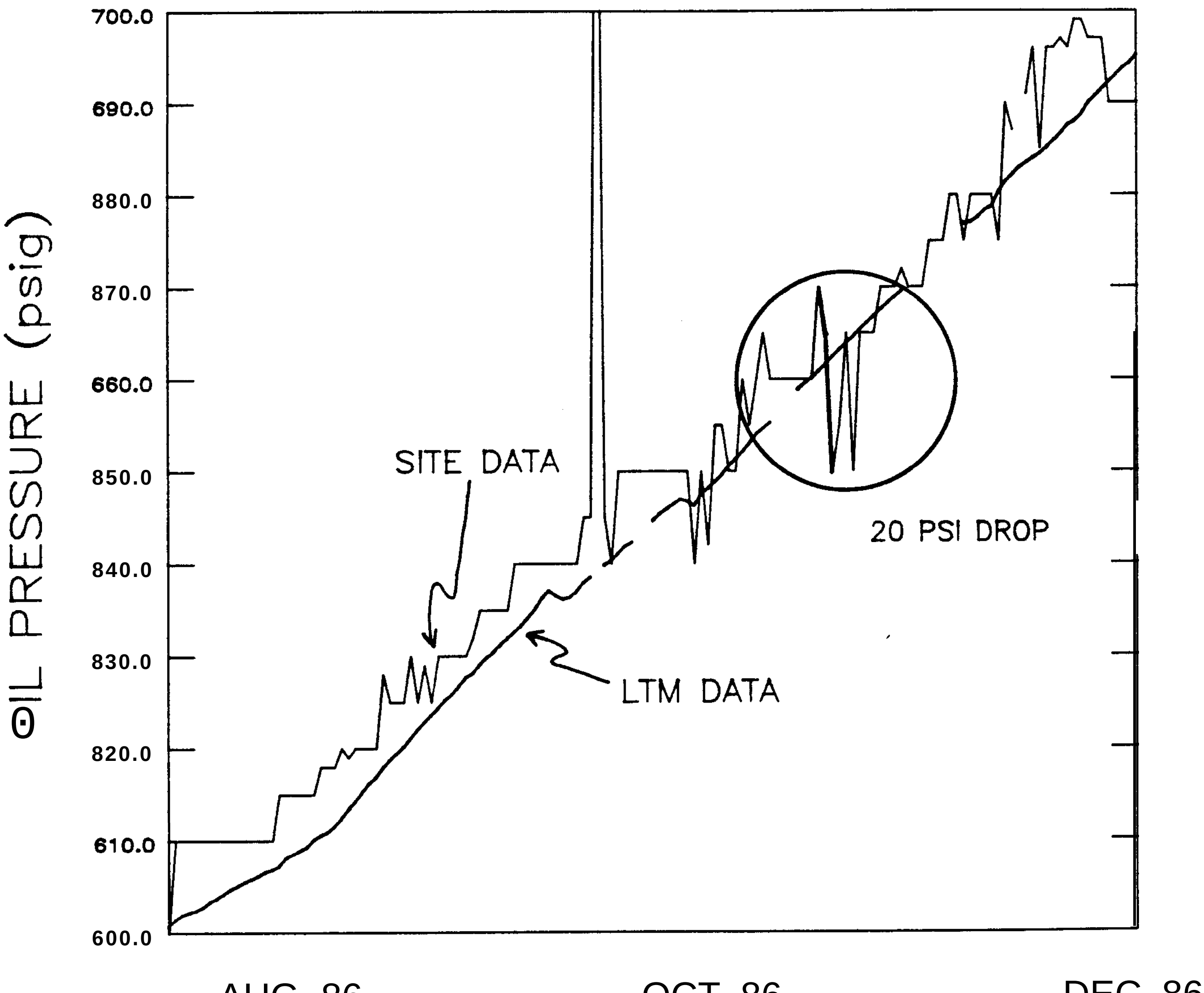
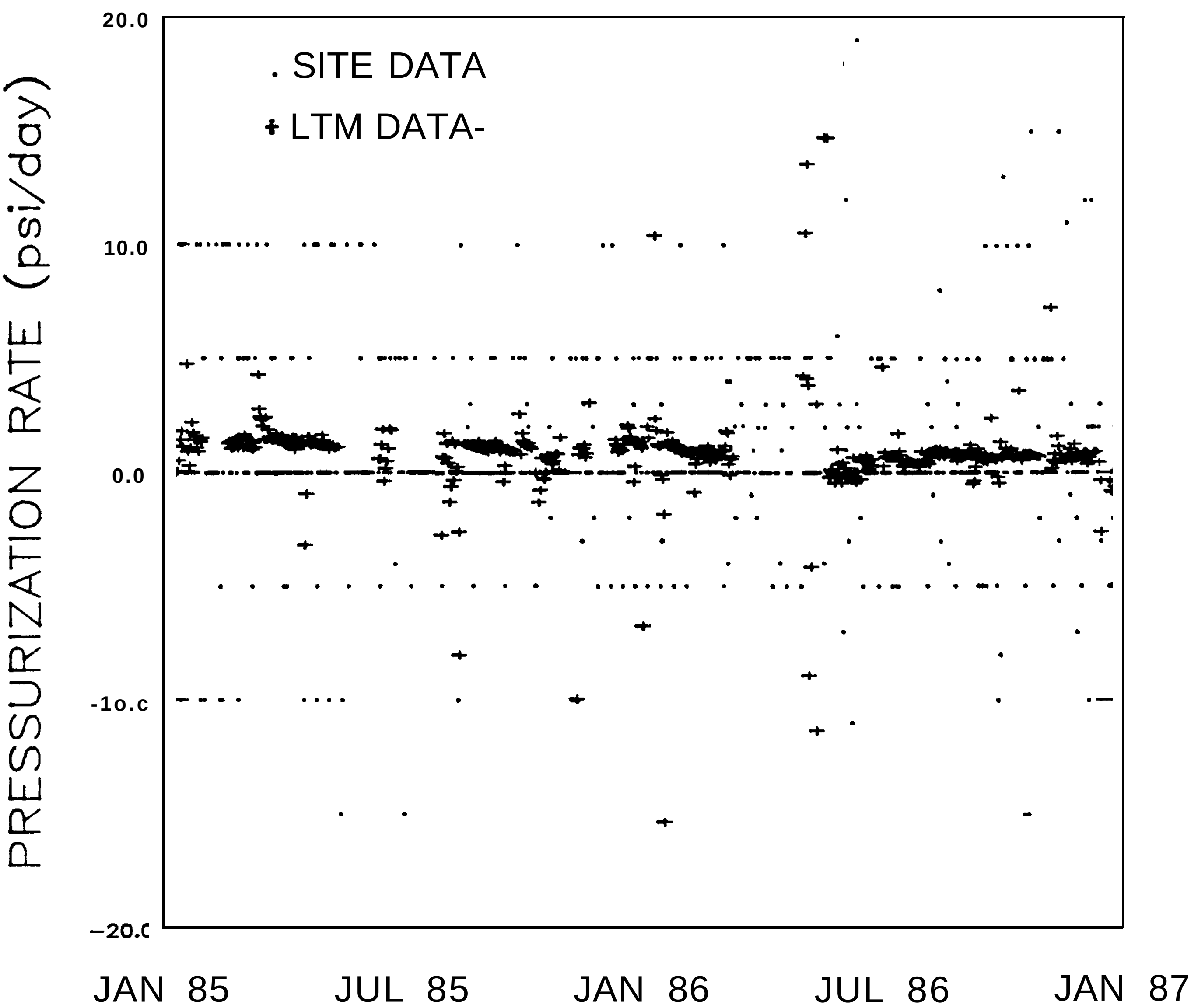


FIGURE 14—

COMPARISON OF CAVERN 1 IO
LTM AND SITE PRESSURIZATION RATES



change in the difference between oil and brine surface pressures is equivalent to six feet of interface movement, it is clear that accurate pressure readings are needed if pressure is to be used as an accurate measure of interface movement.

Summarv and Conclusions

The Strategic Petroleum Reserve caverns are dynamic. Even after placement in their storage mode a number of factors are acting on the caverns and the pressure readings obtained from them. These include temperature changes in the fluids and salt, creep movement of the salt, fluid transfers, oil withdrawals, and other operational impacts. An understanding of these factors and their relationships is essential in order to understand normal cavern behavior. Only by understanding these normal influences can the caverns be monitored for anomalies. Even with two years of data there is insufficient information to determine uniquely the exact impacts of each of the model parameters on the pressurization rate. Although good model fits are achievable, with the data available it is not always possible to distinguish between model deficiencies and abnormal cavern pressurization. However, pressure measurements still provide the most accurate insight into cavern behavior on a continuing basis. Review of the data from Bryan Mound caverns has shown that timely pressure data collection and analysis are an essential part of cavern monitoring. With state-of-the-art pressure monitoring equipment, high resolution pressure data can be achieved which permit more rapid detection of pressure anomalies. This enables site personnel to assess and correct any problems sooner. Because of the need to account for so many cavern pressure influences, review of the data has shown that stable storage mode operation is necessary for development and effective use of pressurization models.

Recommendations

A primary goal of cavern monitoring is to detect changes in the cavern that could be indicative of cavern fluid loss. There are a number of operational recommendations that could help achieve that objective.

The first operational recommendation is to minimize activities which affect cavern pressurization. These include items such as pressure tests, pressure bleed downs, fluid transfers, and oil withdrawals. These activities represent discontinuities in the cavern pressure history which make it more difficult to detect changes in long-term pressurization. Although these activities are required periodically, pressure discontinuities can be minimized if these activities can be scheduled together. The oil pressure histories of Caverns 101 and 112 shown in Figures 15 and 16 point out the difficulty in developing an understanding of pressure history when too many operational impacts are present.

A second operational recommendation is to quickly repair conditions affecting the quality of pressure data collected. This includes repairing or replacing defective gauges and repairing known wellhead or piping leaks

FIGURE 15-

CAVERN 101 SITE OIL PRESSURE DATA

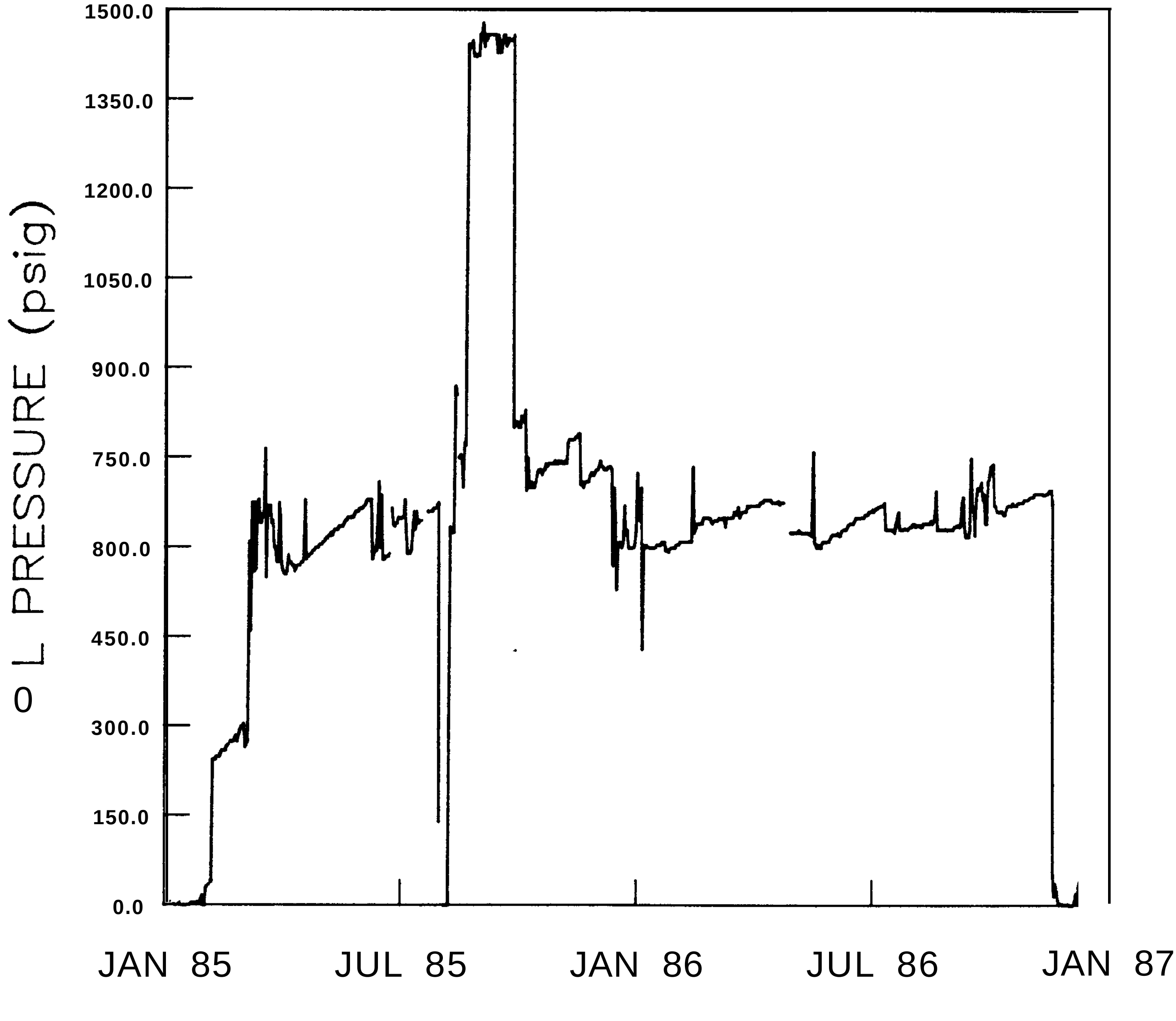
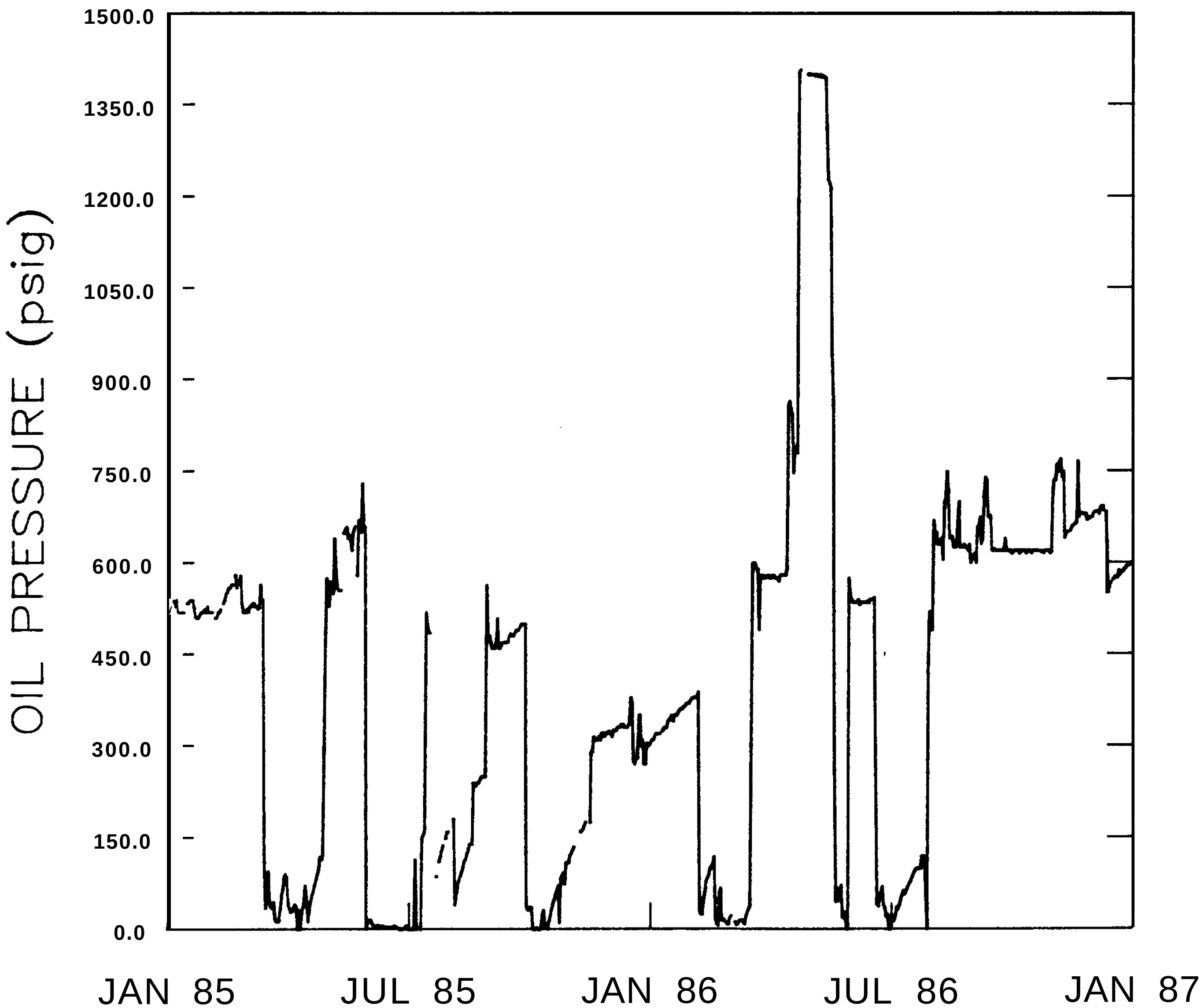


FIGURE 16—

CAVERN 1 12 SITE OIL PRESSURE DATA



which, as shown earlier, can lead to long periods in which nothing is known about the true cavern pressures.

A third recommendation is to standardize pressure operational procedures on each cavern. If the absolute pressure level can be maintained within a fixed pressure range, e.g. 600-700 psi, then the variability of the pressure operational range can be eliminated as a model parameter. Similarly, if the bleeddowns in pressure are always a fixed amount, e.g. 100 psi, and always done over a fixed time period, then the relaxation phenomenon can be considered the same for each of the pressurization intervals. In this manner, changes in cavern pressurization rate can be more easily discernable. Until such operational procedures can be implemented there is a need to periodically update the empirically fitted cavern physical models that have been derived based on available data.

In addition to operational recommendations, there are monitoring recommendations that can be made as a result of these analyses. The first recommendation is that daily reviews of pressure data from each cavern be made.

Second, continuous data collection, with recording every two hours, is appropriate. Continuous monitoring allows sudden dramatic pressure changes to be quickly alarmed, while two-hour data provide a data base sufficient to document most cavern activities or anomalies. Two-hour data can be averaged for daily pressure analyses which should be sufficient for all but periods of known problems.

Third, high resolution pressure data recording should be implemented to enable continued model development and accurate field monitoring.

Fourth, site temperature data should also be collected so that gauge temperature corrections can be included.

Fifth, the addition of brine pressure data provides a degree of redundancy to oil pressure measurements by allowing comparison of pressurization rates. It may also be useful in monitoring oil and brine pressure differences as a measure of interface and other cavern operational changes.

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[2] "PB-KBB Inc. Weekly Report," SPR site activity report prepared for Boeing Petroleum Services, 1985-1986.

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Appendix-

Summary of Cavern Histories 1985-1986

for Bryan Hound Caverns 2, 101, 110, 112

Compiled from Weekly Site Reports [2]

SIGNIFICANT CAVERN ACTIVITIES FOR BRYAN MOUND CAVERN 2, 1985-1986

Activity	Dates Reported
Cavern Workover, Depressurized	5/8/85 - 5/22/85
Cavern Certification Nitrogen Test	5/29/85 - 7/24/85
Partial Cavern Drawdown	12/19/86

SIGNIFICANT CAVERN ACTIVITIES FOR BRYAN MOUND CAVERN 101, 1985-1986

Activity	Dates Reported
Depressurized for Workover	1/3/85 - 2/6/85
Well Maintenance	2/13/85 - 3/6/85
Oil Injection	3/13/85 - 4/10/85
Oil Injection	6/12/85 - 7/17/85
Wellhead Maintenance	8/7/85
Pressure Testing	8/14/85 - 9/18/85
Brine Valve Floating on Header	10/16/85
Pressure Bleeddown	11/20/85
Oil Transfer	12/13/85
Drawdown Test	1/10/86
Raw Water Bled from Column	1/24/86
Oil Injection	2/14/86 - 2/28/86
Oil Injection	5/2/86
101C Brine Pressure Anomaly	6/27/86
Oil Injection	9/12/86 - 10/10/86
Depressurized for Workover	11/21/86 - 1/2/87

SIGNIFICANT CAVERN ACTIVITIES FOR BRYAN MOUND CAVERN 110, 1985-1986

Activity	Dates Reported
Pressure Bleeddown	3/11/85
Pressure Bleeddown	6/12/85
Leaking Motor Valve on Brine Line	7/85
Oil Transfer from Sumps, Bleeddown	9/25/85
Pressurize	10/8/85
Pressure Bleeddown	12/4/85
Pressure Bleeddown	12/18/85
Pressurize	1/1/86
Pressure Bleeddown	1/5/86
Drawdown Test Sale	1/10/86
Pressure Bleeddown	1/16/86
Pressure Bleeddown	3/11/86
Pressure Test	5/23/86 - 6/9/86
Drawdown Test	12/19/86

SIGNIFICANT CAVERN ACTIVITIES FOR BRYAN MOUND CAVERN 112, 1985-1986

Activity	Dates Reported
Oil Injection	1/3/85
Oil Injection	2/27/85
Oil Injection	3/13/85
Depressurized for Wellhead Maintenance	3/20/85 - 5/1/85
Oil Injection	5/8/85 - 6/5/85
Depressurized for Workover	6/5/85 - 7/3/85
Oil Injection	7/17/85
Depressurized for Wellhead Maintenance	7/24/85
Casing Failure 112 A	8/18/85
Oil Injection	9/4/85
Workover 112 A	10/2/85 - 10/23/85
Wellheads 112 A,C isolated from Manifold	10/30/85
Wellheads piped to manifold	11/13/85
Depressurized for Valve Replacement	2/7/86 - 3/14/86
Oil Injection	3/21/86
Hydrostatic Testing	3/21/86 - 4/18/86
Nitrogen Testing	4/25/86 - 5/9/86
Depressurized for Valve Replacement	5/23/86 - 5/30/86
Depressurized for Valve Replacement	7/25/86
Return to Static Pressure	8/1/86
Oil Injection	8/1/86 - 9/12/86
Oil Injection	11/14/86 - 11/21/86
Casing Failure 112 A	12/19/86

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